A STUDY OF THE MIXING OF STEADY AND UNSTEADY FLOW IN GASES BY THE HYDRAULIC ANALOGUE

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SUMMARY

A brief discussion of the analogy between flow of a liquid with free surface in a shallow channel and two-dimensional gas flow is given; also the equivalent pulsation frequency for a water and air system is developed. Use of the analogy for studying the mixing of steady and unsteady flow has the following advantages:

(a) Cost is very low compared with similar air tests.

(b) High supersonic Mach numbers are simulated at speeds of a few feet per second, allowing visual observation of transient phenomena.

(c) Equipment used is much simpler.

(d) Observations are possible of flows at changing speed.

The basic equipment used is a water table with unsteady or pulsing flow in the middle of the channel. The test section is 36 inches by 42 inches. A depth survey system is mounted over the test section so a depth survey can be taken in any part of the channel. Photographic methods are used to secure shadographs of the flow.

Seven tests were made using different Mach numbers in the steady and unsteady flow. The results are plotted as a series of graphs showing the amount of disturbance caused by the unsteady flow in the channel. Shadographs of each condition of flow are shown with the gate at four different positions in the cycle.

INTRODUCTION

The analogy between pressure waves in a compressible gas and gravity waves on the free surface of a liquid have long been known in a general way. That this analogy might be used to study two-dimensional gas flows by means of experiments with a rectangular water channel seems first to have been suggested by Jouguet, Riabouchinsky and von Karman. A detailed examination of certain of the theoretical and experimental aspects of the analogy was carried out by Preiswerk.

In recent years the analogy has been further developed because of the ease and low cost as compared to wind tunnel work. The National Advisory Committee for Aeronautics became interested in the hydraulic analogy because it seemed an easy and inexpensive way of studying two-dimensional compressible gas flow; in particular phenomena occurring at air speeds too high for visual observations could be observed at very low speeds (3 or 4 feet per second) in a water channel.

A water channel was designed and constructed in the Langley 8-foot high-speed tunnel in the Spring of 1940. The channel was so constructed that flow fields involving both subsonic and supersonic velocities about aerodynamic bodies could be investigated.

Tests were run at various depths and Mach numbers and with models of various sizes. Tests were made with flow through nozzles

and about circular cylinders.

Shadographs were taken of the flows about circular cylinders and a comparison of these with schlieren photographs shows that the two flows are very similar.

North American Aviation has also done some experimental work with the water channel. Their conclusions were about the same as those mentioned previously. They have developed photographic methods to obtain qualitative information on wave contours. It was found that the wave patterns in water correspond closely to those in air.

So far little work has been done with the water analogy in unsteady flow. It has been used to study the flows that occur in the inlet and exhaust dusts of reciprocating machinery.

The purpose here is to use the water analogy to study the mixing of steady and unsteady flow. This is to be done by the use of a water table with depth survey and photographic equipment. The shadograph or lighting by refraction method will be used to obtain the photographs. From these it is hoped to obtain some idea of the mixing pattern in the flow field.

NATURE OF THE ANALOGY

For the analogy between water with a free surface and flow of a compressible gas to be valid, the following conditions are imposed on the gas:

1. Ideal
2. Adiabatic
3. Frictionless

For the water flow:

1. Frictionless
2. Incompressible
3. Water flowing over a horizontal bottom under the effect of gravity
4. Surface is free
5. Sides bounded by vertical walls

From the energy equation for water:

$$V^2 = 2g(d_o - d)$$

d_o = stagnation depth of water

d = depth of water

$$V_{max} = \sqrt{2gd_o}$$

From the energy equation for gas:

$$V^2 = 2g(h_o - h) = 2g\ C_p(T_o - T)$$

$$V_{max} = \sqrt{2gh_o} = \sqrt{2g\ C_pT_o}$$

Equating V/V_{max} for air to V/V_{max} for water

$$\frac{\sqrt{2g(d_o - d)}}{\sqrt{2gd_o}} = \frac{\sqrt{2g(h_o - h)}}{\sqrt{2gh_o}} = \frac{\sqrt{2g\, C_p(T_o - T)}}{\sqrt{2g\, C_pT_o}}$$

$$\frac{d_o - d}{d_o} = \frac{h_o - h}{h_o} = \frac{T_o - T}{T_o}$$

Equation of continuity for water

$$\frac{\partial(ud)}{\partial x} + \frac{\partial(vd)}{\partial y} = 0$$

For two dimensional gas flow

$$\frac{\partial(u\rho)}{\partial x} + \frac{\partial(v\rho)}{\partial y} = 0$$

or from these

$$\frac{d}{d_o} = \frac{\rho}{\rho_o}$$

For isentropic flow in gas

$$\frac{\rho}{\rho_o} = \left(\frac{T}{T_o}\right)^{\frac{1}{\gamma-1}}$$

$$\frac{\rho}{\rho_o} = \frac{d}{d_o} = \frac{T}{T_o}$$

$$\frac{T}{T_o} = \left(\frac{T}{T_o}\right)^{\frac{1}{\gamma-1}}$$

Therefore analogy requires that $\gamma = 2$ or in other words for the analogy to be valid the specific heat ratio must be 2.0.

The velocity of the water flow is very small in comparison with the velocity of sound in air. Velocity of sound in water plays no part at all in the analogy.

The analogy depends upon the wave propagation velocity:

$$A = \sqrt{gd}$$

where g = acceleration of gravity

d = depth of water

On the basis of this wave propagation velocity the water may be divided into two divisions, which as in the case of gases differ essentially in their characteristics. If the water velocity is less that $\sqrt{gd}$ the water flow corresponds to "subsonio flow" and if the water velocity is greater than $\sqrt{gd}$ the water flow corresponds to "supersonic flow" of gases.

Inasmuch as the analogous relationships depend upon the depth of the water and no other variable remains to represent a third dimension, the hydraulic analogy is strictly limited to two-dimensional phenomena.

For channel flow without hydraulic jumps, the analogy to gas flows without shocks is limited only by the validity of the

assumptions made in development of the equations of motion. These assumptions are sufficiently accurate for all practical purposes. However the analogy between hydraulic jumps in the channel and shocks in air involves discrepancies which can no longer be neglected. The first is due to the difference in γ, which has the value of 1.4 for air and the value of 2.0 for the water channel, as explained previously. If the deflection producing the shock is small the wave angle will be nearly independent of γ .

The second type of anomalous behavior is due to loss of mechanical energy in the hydraulic jump. This loss is so called because it raises the temperature of the water. The water temperature has no analogous quantity in the gas flow (the gas temperature corresponds to the water height). Thus in a hydraulic jump there is always a loss in total head, or energy, of the water which does not exactly correspond to the total pressure loss in a shock wave. This loss in head may be found by applying the "energy" equation, since the conditions after the jump are determined by the equations of momentum and continuity alone.

For the analogy with unsteady flow it is necessary to find a dimensionless frequency of pulsation which is the same for both systems. Considering first the flow system if it were air. The length of the flow system is 42 inches. In a pulse jet engine the

frequency of pulsations is equal to the speed of sound divided by 4 times the length of the engine behind the valve grid. Assuming the speed of sound was 1120 feet per second, this gives the pulsation frequency as 80 cycles per second. The time of each pulsation in the air system would be the reciprocal of 80 or .0125 seconds. Combining these gives the dimensionless frequency of 1.

For the water system with a 1/4 inch depth the wave propagation velocity is 9.82 inches per second. Combining this with the length of the flow system as above gives a time of 17.1 seconds for each cycle. This combined with the pulsation frequency in the water system must be equal to the dimensionless frequency of 1 obtained for the air system. Solving for the water pulsation frequency it is found to be .0584 cycles per second or 3.5 cycles per minute.

Summary of Analogy

Significant quantities and characteristics of 2 dimensional compressible gas flow, $\gamma = 2$		Corresponding values in analogous liquid flow	
Temperature Ratio	T/T_o	Water depth ratio	d/d_o
Density Ratio	ρ/ρ_o	Water depth ratio	d/d_o
Pressure Ratio	p/p_o	Square of water depth ratio	$(d/d_o)^2$
Velocity of sound	$a = \sqrt{\frac{\gamma p}{\rho}}$	Wave velocity	$\sqrt{gd}$

Mach number V/a	Mach number $V/\sqrt{gd}$
Subsonic flow	Streaming water
Supersonic flow	Shooting water
Shock waves	Hydraulic jump

WATER DEPTH

There are two types of waves that are found on the free surface of the water. They are capillary waves and gravity waves.

Capillary waves are largely caused by the surface tension of the water. The water surface acts as a stretched membrane and disturbances in the surface are propagated as capillary waves of small wave length and large propagation speed. These waves are not a part of the analogy.

In water channel experiments, the capillary waves are important chiefly as a nuisance in making height measurements and in interpreting photographs of wave patterns.

The distinction between capillary and gravity waves is best made by means of the general velocity wave-length relations for waves in shallow water.

$$V^2 = \left(\frac{gh}{2\pi} + \frac{2\pi T}{\rho \lambda} \right) \tanh \frac{2\pi h}{\lambda}$$

where

ρ = gm/cc

T = surface tension

g = 980 cm/sec^2

If the wave length λ is large the waves are called gravity waves and the wave velocity approaches the asymptote $\sqrt{gh}$. If a

plot of wave velocity against wave length is made for different water depths it can be seen by employing a water height in the neighborhood of $\frac{1}{4}$ inch, the minimum propagation speed is approximately the same as the speed of the long gravity waves, which suggest this height is the most appropriate from the standpoint of the analogy.

PHOTOGRAPHIC METHODS

In order to better interpret the results several methods of photographing the water surface have been developed. A brief description of the lighting and experimental techniques will be given.

One of the earliest methods of obtaining photographs of the water surface was to use lighting by reflection. Some of the arrangements to secure this are as follows:

(1) Spotlights or flood lights directed at various angles to the surface.

(2) Floodlight illumination through a four-foot square diffusing screen above the channel, with the camera at a hole in the center of the screen.

(3) Illumination of the same screen from below.

The above systems all give barely usable results. The major difficulty is in the interpretation of the photographs.

Another method is lighting by refraction. This depends on light which passes once or more through the upper surface of the water. On crossing this surface, the rays are in general deflected by refraction by an amount depending on the slope of the surface at each point.

If waves in a channel with a white bottom are illuminated

by a small source of light at a distance, a pattern of shadows may be seen on the bottom. These may be photographed from above or below. Placing the translucent screen (opal glass in this case) above the surface and illuminating from below is equally effective. This system is extremely sensitive to small distortions of the water surface. This sensitivity can be reduced to a practical value and the screen eliminated by replacing the point source with a diffused light. This is an excellent method of obtaining photographs if the channel has a transparent bottom.

Of the photographic methods the absorption method is capable of giving accurate quantitative information on wave contour. This method is based on using a certain kind of dye in the water and this causes the wave crests of the water to appear darker on the negative than the wave troughs. By photometric measurements on the negative film, it is possible to obtain quantitative information on the contours of the waves in any region with little difficulty.

APPARATUS AND EQUIPMENT

The design of a water channel is somewhat similar to that of a wind tunnel. The water flows from a large quieting section into a test section and then is returned to the quieting section by means of some circulating system.

There are two main types of water channels, the horizontal return type and the vertical return type. In this case a vertical return was chosen.

In this water channel the large quieting section is represented by the large reservoir as shown in Figure 1. From this the water flows under a gate into the test section which is the large plate glass. From the test section it flows into the small overflow reservoir as seen at the left end of the figure. From the overflow reservoir the water is returned to the main reservoir by means of a pump.

The frame was constructed of 2-inch angle irons. These were chosen because they were rigid enough to keep the frame from warping. To support the glass test section 2-inch T irons were used. The upper part of one side of the T was removed in order that very shallow water could be observed from the side. Small pieces of iron were welded into the angle in the bottom of the leg. These were threaded and 1/2 inch bolts inserted. This was done to give the proper level and tilt to the table.

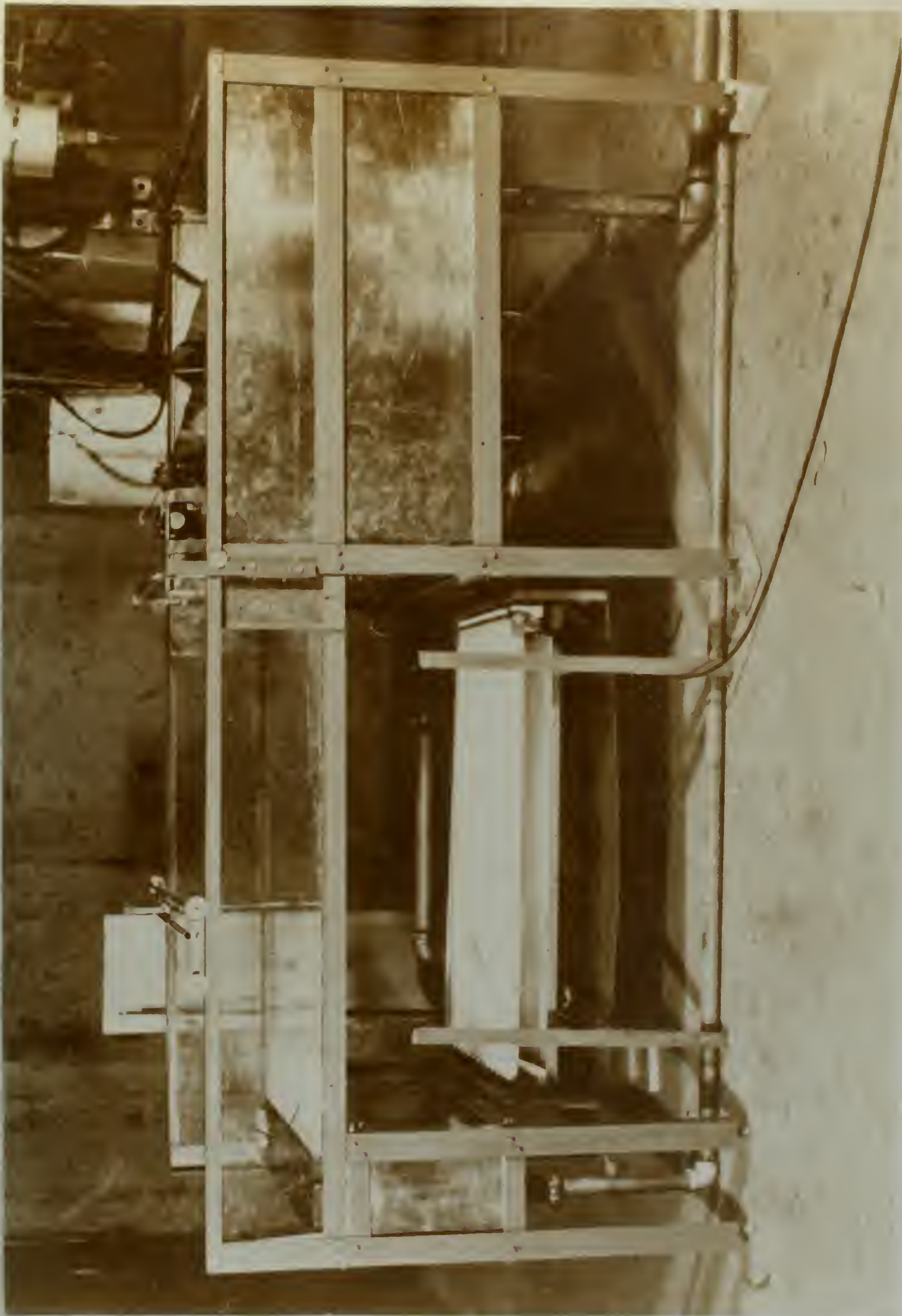


Fig. 1. Side view of water table.

The frame that holds the return reservoir is not rigidly fastened to the main frame. It is held by only one bolt at each joint so it can swing free and cause no strain on the glass.

The top iron that serves as a track for the measuring device is a 1-inch angle. It also protects the top edge of the glass sides. All of these can be seen in Figure 1. The tanks are supported in their frames not only by the angle irons but also by three cross supports spaced evenly across the frame. This prevents most of the sag in the tanks due to the weight of the water.

The main reservoir or quieting section is $36\frac{1}{2}$ inches by $35\frac{1}{2}$ inches. It is so constructed that 12 inches of it is below the test section level and merely acts as a quieting or dampening agent. It extends 7 3/4 inches above the test section level so this amount of total head is obtainable. There is a 2-inch pipe in the bottom of the reservoir to admit the return flow from the pump. Also there is an adjustable overflow pipe. This is a $1\frac{1}{4}$ inch pipe that fits snugly inside of another. It can be moved so as to maintain any total head desired. For fine adjustments there is a small pipe that fits over the top and is threaded. This can be raised and lowered 1 inch by the threads and will give the fine adjustment desired. The overflow goes into the main floor drain and is not used again. This can be seen in Figure 1 as the pipe

coming out of the bottom of the main reservoir and running along the floor to the drain. This main reservoir is fastened to the plate glass sides and bottom. To attach the reservoir to the plate glass test section a 6-inch piece was folded back into the tank. Then the plate glass was placed so as to extend back into the tank. This can be seen in Figure 4.

The tank and brass were fastened together by using two rows of No. 5 machine screws, the screws being 2 inches apart each way. To seal between the two 3-M trim cement was used before the screws were tightened. The tank sides were made 4 inches longer so they overlap the glass sides by that much. They are fastened together in same way as the bottom.

The test section is made of $\frac{1}{4}$ inch plate glass. The bottom piece is 36 inches by 48 inches, giving a test section 36 inches by 42 inches. The other 6 inches of glass extends up into the main reservoir as was mentioned above. There is a small strip of rubber between the frame and the glass to avoid chipping and breaking.

The sides of the test section are also $\frac{1}{4}$ inch plate glass. They are 48 inches by 8 inches. They are fastened to the copper tank as described above. The glass sides fit snug against the glass bottom and are sealed by using 3-M trim cement.

From the test section the water flows into a small return

reservoir. This reservoir is 36 inches by 8 inches and 12 inches high. There is a 2-inch pipe out of this that leads to the pump. There is also an overflow pipe that leads to the floor drain as seen in Figure 1. The glass bottom ends 6 inches short of the end of the table and this allows the water to flow into the reservoir.

The tank that furnishes water for the unsteady or pulsing flow sets in the main reservoir. It is 31 inches by 6 inches and 18 inches high. As in the main reservoir there is 12 inches of water below the test section level. The pulse tank is constructed the same as the main reservoir with a 1-inch overlap past the gate. This was done to allow the gate to be all one piece. The tank sets in the middle of the main tank so there is equal amount of steady flow on both sides of it. A general idea of the set-up can be seen in Figure 2. The maximum head here is 5 3/4 inches. This also limits using more than this amount of head for the main reservoir. This tank is fastened to the glass in the same manner as the main tank, the same screws extending through both tanks. The seal between the side of the tank and the top of glass (in Figure 4) was made by using a small strip of brass with a piece of rubber under it. This was bolted to tank and the rubber allowed to extend down to the glass to form the seal. Fresh water is brought into the system by a pipe into this tank. This can be seen as the smaller pipe on the right in Figure 2. The other pipe is 3/4 inch pipe

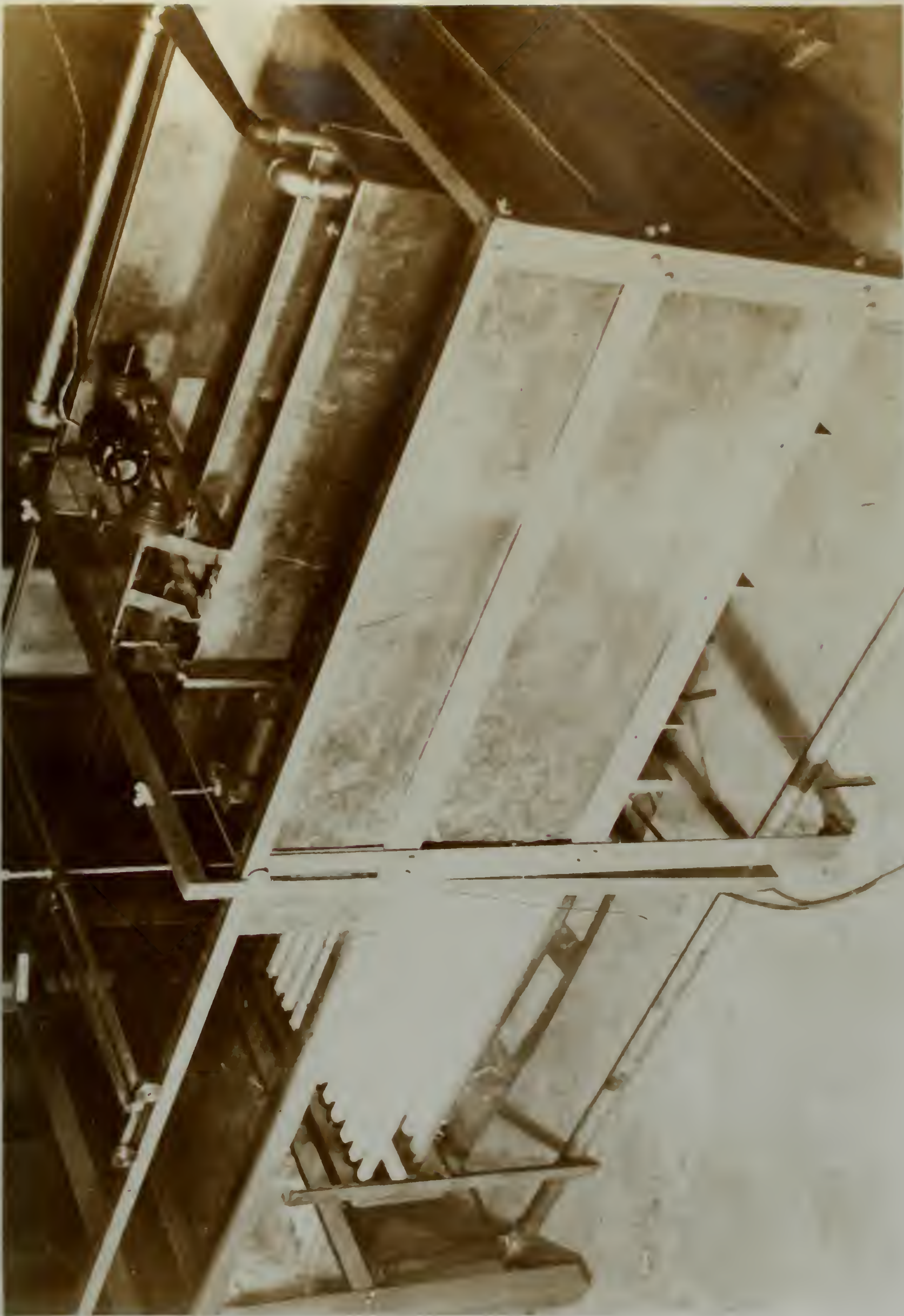


Fig. 2. Bird's-eye view of water table.

leading from a T fitting on the main pumping system.

The circulating system consists of a pump and system of valves to split the flow between the main reservoir and the pulse reservoir. The pump is a low pressure, high output design powered by a 3/4 horsepower, 220 volt alternating current motor. It takes the water from the overflow reservoir. The pump has a $1\frac{1}{2}$-inch inlet and outlet. On the pressure side of the pump is a T fitting with a 3/4 inch pipe leading to the pulse tank. After the fitting there is a valve in the $1\frac{1}{2}$-inch line leading into the main reservoir. There is no way to control the speed of the pump so the output is controlled by the two valves. Also the flow can be divided between the two tanks in any manner desired by proper manipulation of the valves. No attempt is made to use the same water all the time. Some fresh water is allowed to flow in at all times, therefore being assured of having the desired head. Any excess goes out through one of the two overflow pipes leading into the floor drain. The pump was isolated from the water channel by hose connections to cut down the vibrations. The pump was also mounted on a rubber pad for the same reason.

A close-up of the circulating system can be seen in Figure 3. The pipe on the right leads out of the return reservoir into the pump. The vertical pipe with the valve leads into top of the pulse tank and the larger pipe goes into the bottom of the main

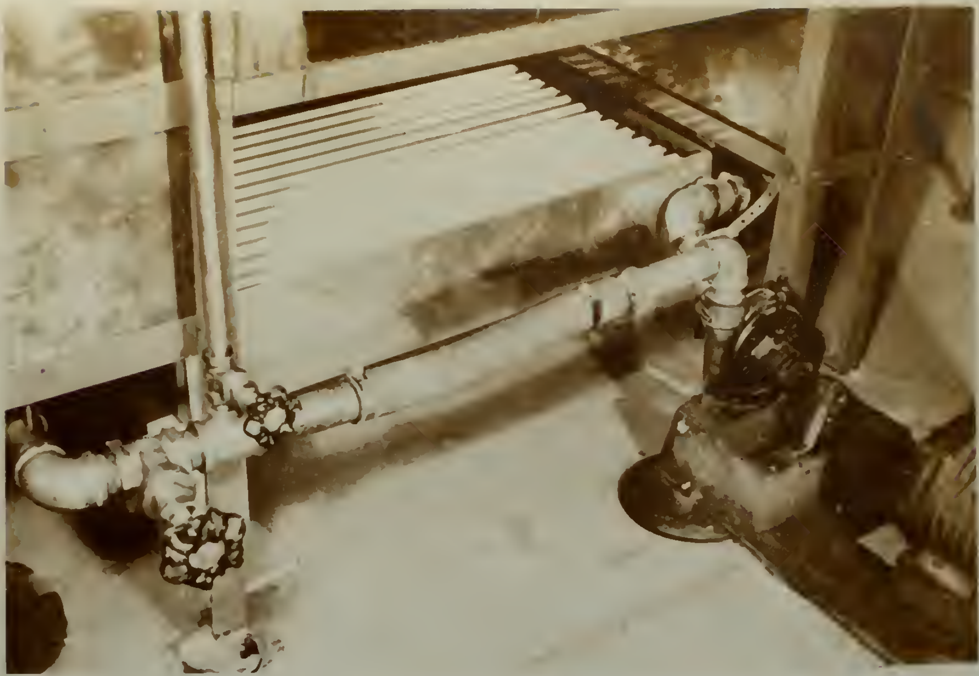


Fig. 3. Water circulating system.

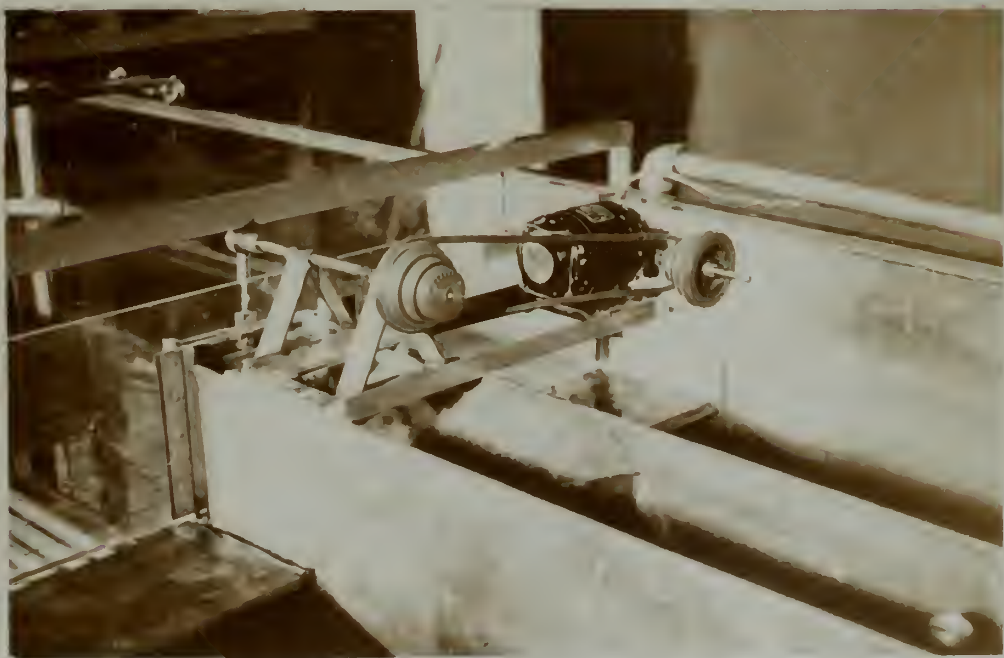


Fig. 4. Unsteady flow gate with motor.

reservoir. A part of the motor can be seen at the lower right hand corner. The pipe leading into the main pulse tank goes to the bottom of the tank so the water coming out will cause the minimum disturbance to the surface. In the main tank a small flange about 1-foot square is placed directly over the return pipe from the pump. This cuts down the disturbance and spreads out the water ejecting from the pipe.

The main gate is made of $\frac{1}{4}$-inch plexiglass. The gate sets against the two glass sides and is held in place there by the water pressure. The gate is made so that it fits right over the pulse tank. By looking at Figure 4 this can be clearly seen. The gate is supported by a rectangular frame that is bolted to the main frame. The gate can be raised and lowered by the nuts on the bolts fastened to the gate and extending through the frame as seen in Figure 4. There are also nuts on the bottom of the frame so when both nuts are tight the gate is held rigid at one setting. The gate can be raised to a maximum height of two inches. In order to cut down on the edge effect the edge of the plexiglass is beveled at a 45 degree angle on the test section side. To seal the gate rubber strips were bolted to the gate by using small brass strips. The rubber was allowed to overlap and form the seal when the gate is in place as seen in Figure 4.

To obtain the unsteady or pulsing flow a sliding gate is

used in the pulse tank. This is also made of plexiglass and different views of it can be seen in Figures 4 and 5. The gate is raised and lowered by an eccentric arm driven by a 24 volt, direct current motor. By means of a rheostat and pulleys any speed may be obtained up to 1200 revolutions per minute. The gate can be set to raise to maximum height of 3/8, 1/2, or 5/8 inch. The arm is adjustable so it is possible to get the gate to fit solid against the plate glass when it is in the closed position.

The depth survey system can be seen in Figure 5. It consists of a micrometer head mounted so that it slides back and forth on the two rods shown. The whole system is mounted on four wheels and rolls on the 1-inch angle irons that act as a protector for the glass edges. This makes it possible to get a depth survey in any portion of the test section. The micrometer reads to thousands of an inch.

To facilitate measurements and to have some pattern to follow a grid was painted on the under side of the plate glass in the test section. This was done by using a small paint striper that makes a 1/8 inch stripe. The grid consists of 2-inch squares. The pattern can be seen in Figure 5.

Copper was the material used to make all the tanks. Brass was used for the measuring apparatus and as holders for the gate. The iron framework was painted to prevent rust.

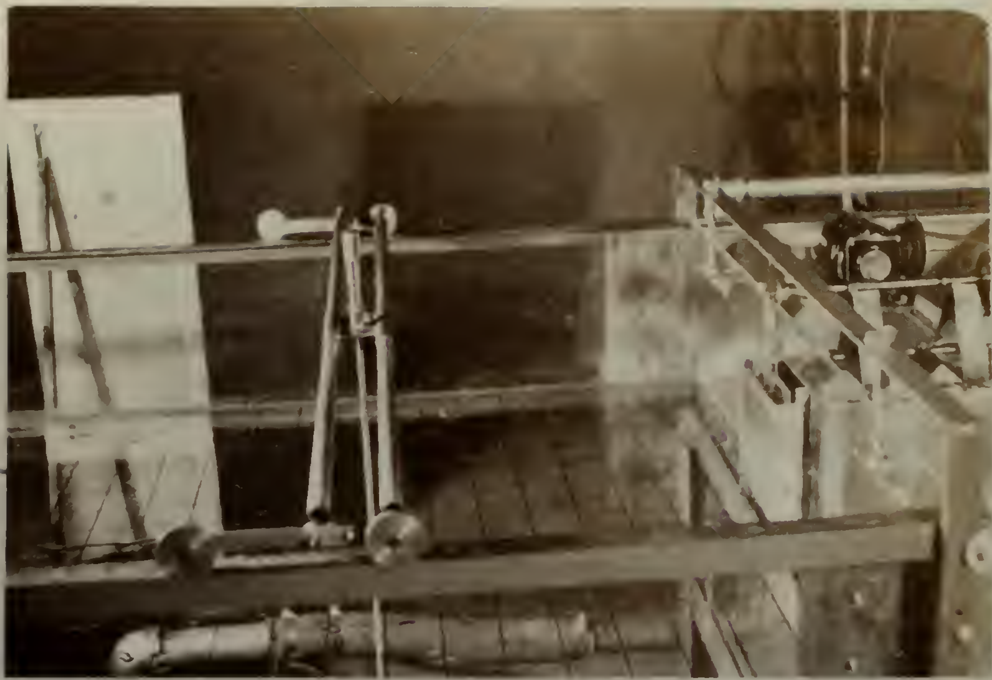


Fig. 5. Depth survey equipment.

Fig. 6. One of the photographic set-ups.

To obtain shadographs of the flow several different types of photographic equipment was tried. One system is shown in Figure 6. This lighting unit here consists of a bank of floures-cent lights, 12 30-watt tubes 36 inches long. This was capable of delivering 400 candle power at a distance of 3 feet.

Another light source consisted of a roflector with a No. 2 photoflood bulb. These were mounted under the plate glass.

A piece of opal glass 20 inches by 36 inohes was suspended 1 inch above the water and the wave patterns were shown on this. A 35 millimeter kodak with a 1/200 of a second shutter was used to take the photographs.

CALCULATION OF MACH NUMBER IN CHANNEL

In a water table of this type the velocity of the water in the test section is determined by the head of water in the reservoir.

From Toricelli's theorem, the velocity of the water is

$$V = \sqrt{2g(d_o - d)}$$

and

$$M = \frac{V}{\sqrt{gh}}$$

Substituting for V

$$M = \sqrt{\frac{2\ (d_o - d)}{d}}$$

This formula for Mach number was plotted as shown in Figure 7.

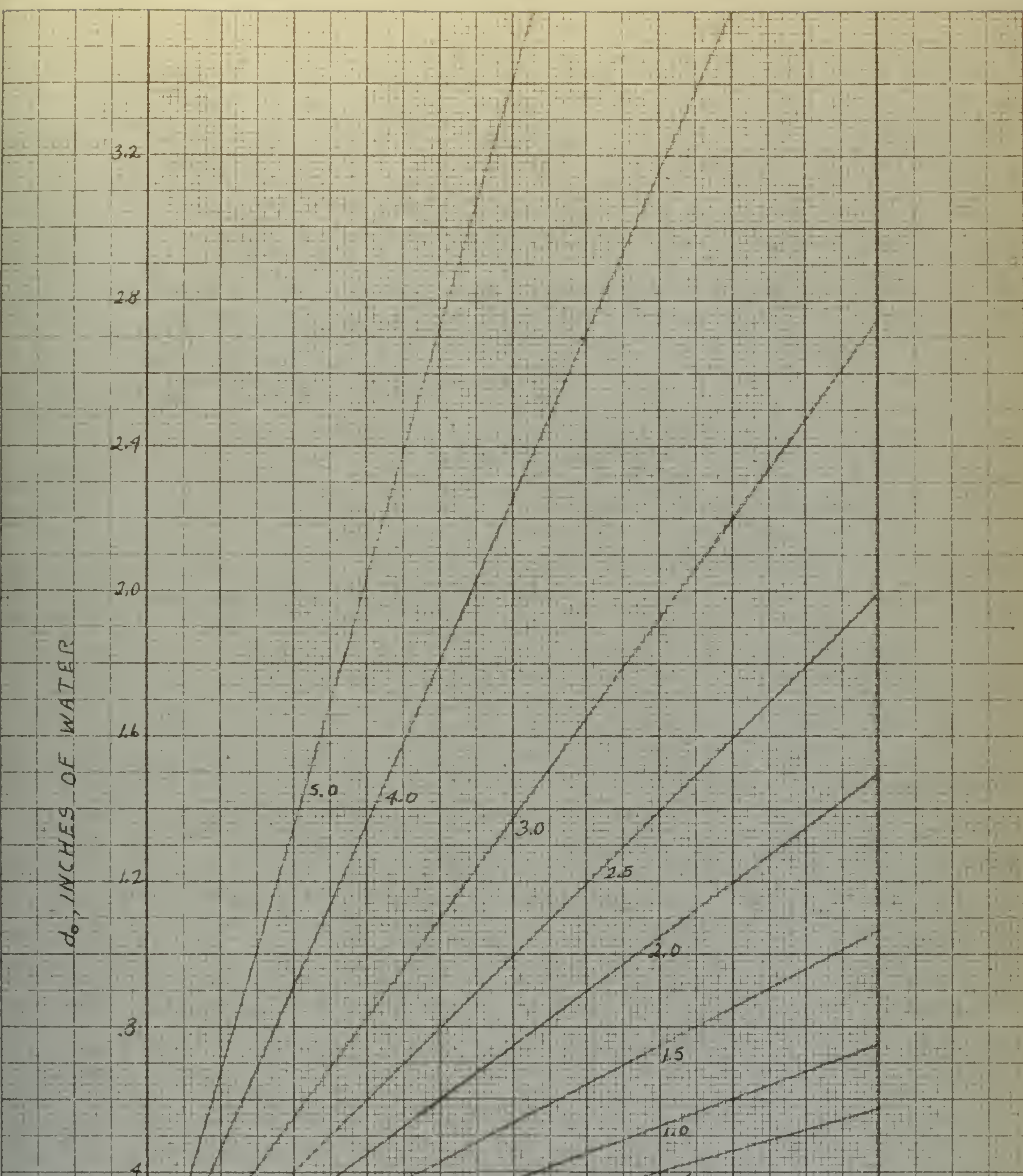


FIG 7 CHART FOR COMPUTING MACH NUMBER IN CHANNEL

PROCEDURE

Before any testing could be done it was necessary to adjust and level the water table. This was done by using the adjustable bolt in each leg. Several levels at different positions were used to get the table perfectly level.

To overcome the decelerating effects of friction on the plate glass the channel was tilted sufficiently to overcome it. This was done by trial and error and a slope of about ½ degree was found to be adequate.

The main gate was adjusted so as to give a flow of ¼ inch depth in the test section. A depth survey was taken just below the gate to be sure the flow was of uniform depth.

The gate in the pulse tank was adjusted to give a flow of 2/5 inch depth. Care was taken to assure that the arm controlling the gate was of the proper length to completely shut off the flow when the gate was closed.

The rheostat controlling the speed of the small motor operating the gate was adjusted to give a speed of 3.5 revolutions per minute.

Tho system was filled with water through the intake pipe in the pulse tank. When both the main reservoir and the pulse tanks were full to the test section level, the water was allowed

to run into the return reservoir by passing over the plate glass test section. When this tank was full, the pump was started. This raised the level of the water in the main reservoir sufficiently to keep the water circulating. The overflow pipes in both the main and pulse tanks were adjusted to give the head of water desired. The valve in the line leading to the pulse tank was adjusted to maintain the head. The valve in the main line was adjusted so as to put through approximately the same amount of water as went out of the main tank through the test section area. This keeps the pump from surging when operating the water table at small water velocities and creating additional disturbance to the surface of the water in the main reservoir. A small amount of fresh water is allowed to flow continuously into the pulse tank and this excess water is taken out through one of the overflow pipes.

Tests were run with the steady flow at a Mach number of one and the unsteady flow at Mach numbers of two, three, four and five. Then the Mach number of the steady flow was increased to two and tests repeated with unsteady flow Mach numbers of three, four and five.

Since the flow is symmetrical, one half of the channel was surveyed in each test. Depth surveys were taken at the centerline and at 4 inches, 8 inches, 12 inches and 16 inches from the centerline of the channel (perpendicular to the flow). The first depth

measurement was taken 3 inches downstream from the gate and repeated every 4 inches down the channel.

At each point a maximum, minimum and zero reading were taken. Then the absolute maximum and minimum depth was obtained by substracting the zero reading from each. The zero reading was necessary at each measurement because the track and wheels of the measuring mechanism were not machined accurately enough for one zero reading or calibration to be used for all the tests.

Maximum readings were taken by adjusting the micrometer until the point just rippled the water. Two or three complete cycles were usually necessary to get this accurately. Minimum readings were taken by sighting along the surface of the water and adjusting the point in the same manner as above. Four or five complete cycles were usually necessary to get this reading accurately.

The first photographic set-up that was tried is shown in Figure 6. The bank of flourescent lights was mounted immediately below the plate glass test section. The opal glass was suspended about an inch above the surface of the water. This did not give the proper lighting and the wave contours were not distinct enough to photograph. Using a piece of ribbed glass over the flourescent bulbs to diffuse the light, the pattern was still not distinct.

Evidently the light was not striking the plate glass test section as parallel rays causing the pattern on the opal glass to be indistinct.

The bank of lights was replaced by a reflector with a No. 2 photoflood bulb. This proved much more satisfactory and gave the patterns shown on later pages. The camera was mounted about four feet above the opal glass.

Shadographs of the flow were taken for each of the seven tests. For each condition of flow, four pictures were taken. These show the flow with the pulse gate starting to open, gate completely open, gate partially olosed and gate completely closed.

RESULTS AND DISCUSSION

From the measurements of the maximum and minimum water heights in the channel, the amount or height of the disturbance can be determined. The amount of disturbance is plotted against distance along the channel for each length of the channel that was surveyed.

Each plot really consists of five graphs as can be seen by referring to Figure 8. These graphs represent the conditions at the centerline and every 4 inches from there to the outside edge. Actually the last measurement is taken 16 inches from the centerline or 2 inches from the edge. The abscissa represents the distance downstream from the jet and the ordinate is the difference between the maximum and minimum heights.

In Figures 8, 10, 12 and 14, where the steady Mach number is 1 and the unsteady Mach number is increased from 1 to 5, a definite pattern of the edge of the disturbance can be noted. The edge of the disturbance starts at a point about 5 inches from the centerline of the jet (perpendicular to flow) and runs in a straight line to a point at the edge of the channel somewhere downstream. The point at which it strikes the edge varies with the speed of flow. This can be noted on the graph as a definite rise in the height of the disturbance. At a Mach number of 2 for the unsteady flow the edge of the flow is unaffected until 23 inches below the

jet. As the Mach number is increased this steadily moves up the channel until at a Mach number of 5 the steady flow is affected 8 inches below the jet. At the other points in the channel the disturbance also moves upstream as the unsteady Mach number is increased. By referring to Figure 13b this disturbance can be seen as the small ripple in the upper left and lower left hand corners.

In all the graphs there is a definite build-up in the height of the disturbance at the lower end of the channel near the edge. This is due to the so-called "piling up" of the water or edge effect.

In the center portions of the channel below the disturbance previously mentioned the height of the disturbances are fairly constant. Of course in all cases the maximum disturbance occurs along the centerline as would be expected. The disturbance reaches a maximum just below the gate. The height of the disturbance at all points increases as the Mach number of the unsteady flow is increased.

There doesn't seem to be any great change in the pattern when the steady Mach number is increased from 1 to 2 as shown by Figures 16, 18 and 20. However, at the same unsteady Mach numbers the edge of the disturbance is pushed farther downstream. This is probably due to the increased velocity of the water in the steady flow.

The shadographs show the patterns at various positions in the cycle for each condition. They do not cover the complete channel since an opal glass screen of the channel size was not available. When the gate is just starting to open there is a definite trend as the unsteady Mach number is increased. As shown in Figure 9a, the water comes out as a small wall and gradually extends itself into the jet. The intensity of the jet is increased with the higher Mach numbers as shown by going from Figure 9b through Figure 15b. The edge of the jet is characterized by a hydraulic jump at the edges. Actually in Figure 9b the jet only extends about 8 inches downstream while in Figure 15b it extends slightly beyond the photograph or about 24 inches. Actually outside the jet the water surface is relatively uniform for that period when the gate is almost fully open to when it is just starting to close.

When the gate is starting to close the jet recedes and two ripples or disturbances break toward the edge of the channel from the point of the jet. The disturbance becomes more pronounced as the unsteady Mach numbers are increased. In the wake of the disturbance there is left practically a stagnation region. The surface is very flat without a ripple.

When the gate is completely closed and the cycle complete, this stagnation area becomes more pronounced. Just aft of the gate

there is a small disturbance due to the water running into this space from the steady flow when the gate is olosed and no water is flowing from the pulse tank. As the Mach number is increased this stagnation area becomes smaller and the ripples or disturbances at the edge do not spread out as much.

Increasing the steady Mach number from 1 to 2 tends to narrow the patterns. This is probably due to the increased velocity of the steady flow.

The shadographs could be improved by using a larger opal glass screen and by the use of a stronger point source of light. It is felt that this would bring out the wave contours more distinctly.

A better idea of the continuous ohange in water height at each position could be obtained if a device were available to continuously record the water height. This could probably be done by using probes with an electric circuit attached to some sort of a recorder but it was beyond the scope of this particular work.

From this analysis it would appear from the analogy that in the mixing of steady and unsteady flow in gases there is a definite area of the steady flow that is affected depending on the velocities of both flows. The continuously changing water heights throughout the channel indicate that there are great pressure

fluctuations in the analogous gas flow. The complexity of measuring such pressure changes is magnified by the speed of the pulsations which in this case is 80 cycles per second. It appears that some electronic device would be necessary to record these pressures if they could be measured.

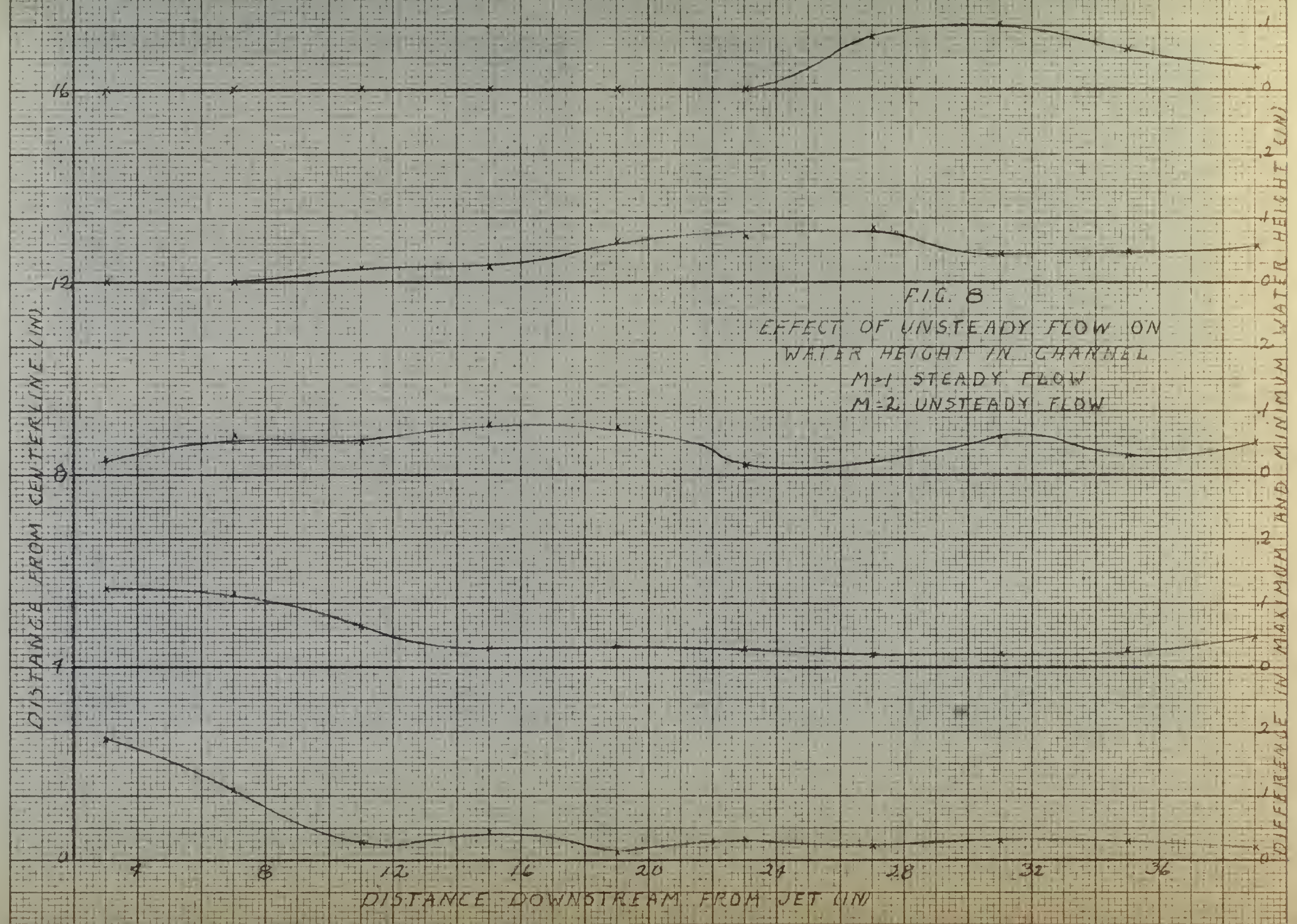


FIG. 8

EFFECT OF UNSTEADY FLOW ON WATER HEIGHT IN CHANNEL

M-1 STEADY FLOW

M-2 UNSTEADY FLOW

a. Gate starting to open.

b. Gate completely open.

c. Gate partially closed.

d. Gate completely closed.

Fig. 9. Unsteady jet flow mixing with steady channel flow. M = 1 Steady flow. M = 2 Unsteady flow.



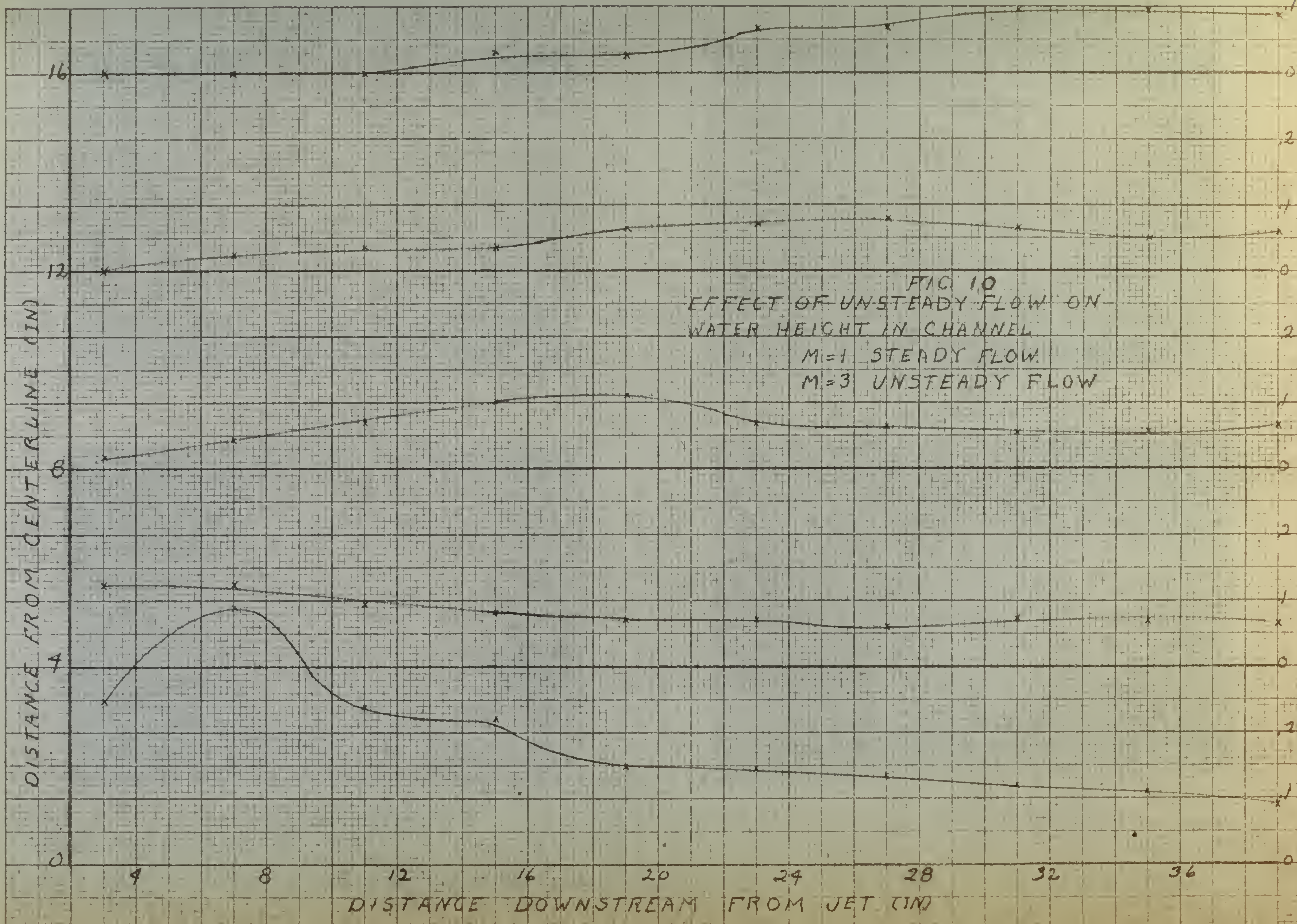



FIG. 10
EFFECT OF UNSTEADY FLOW ON
WATER HEIGHT IN CHANNEL
M=1 STEADY FLOW
M=3 UNSTEADY FLOW
DISTANCE FROM CENTERLINE (IN)
DIFFERENCE IN MAXIMUM AND MINIMUM WATER HEIGHT (IN)
DISTANCE DOWNSTREAM FROM JET (IN)
0
4
8
12
16
20
24
28
32
36
.1
.2

a. Gate starting to open.

b. Gate completely open.

c. Gate partially closed.

d. Gate completely closed.

Fig. 11. Unsteady jet flow mixing with steady channel flow. $M = 1$ Steady flow. $M = 3$ Unsteady flow.

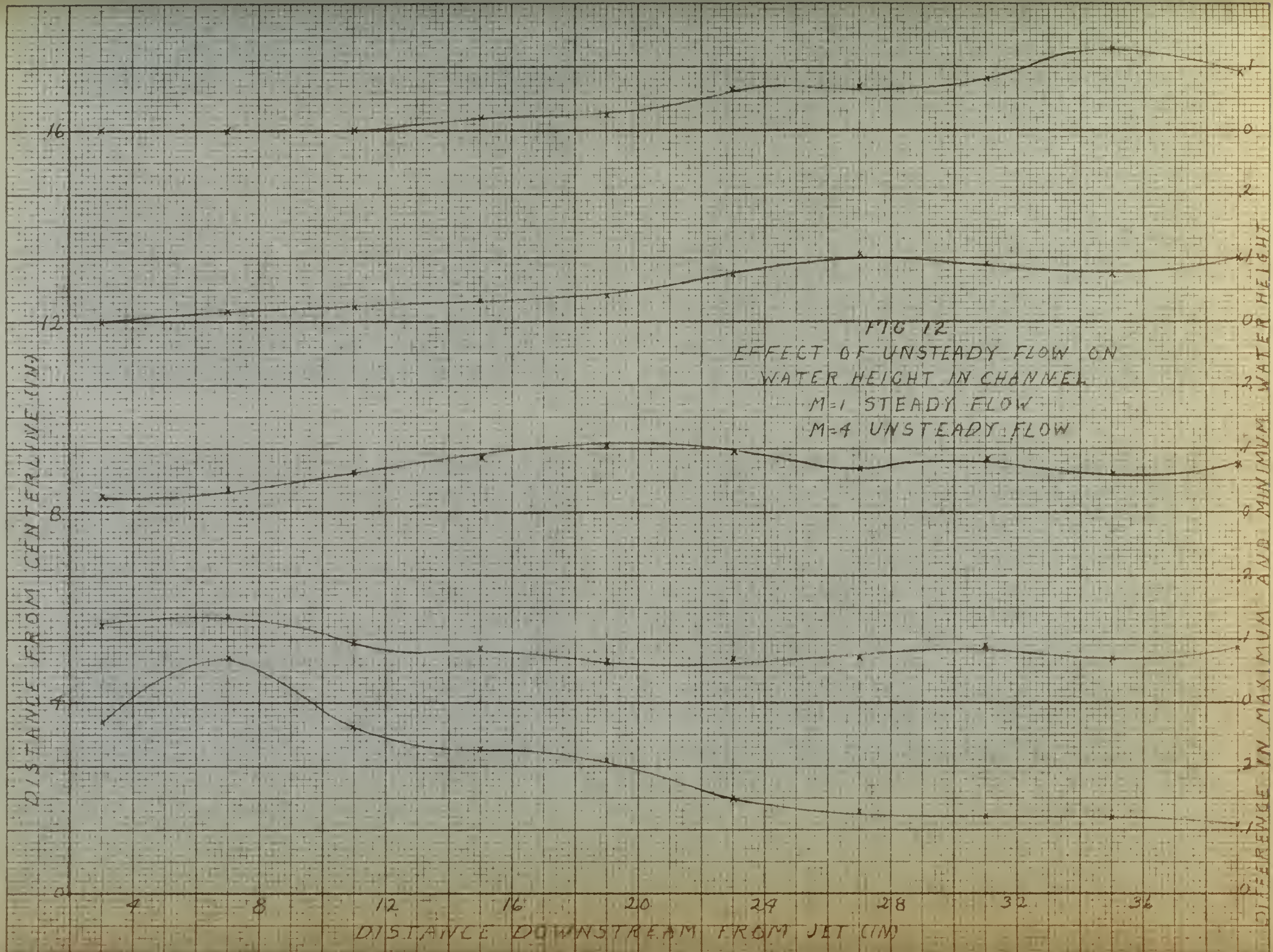
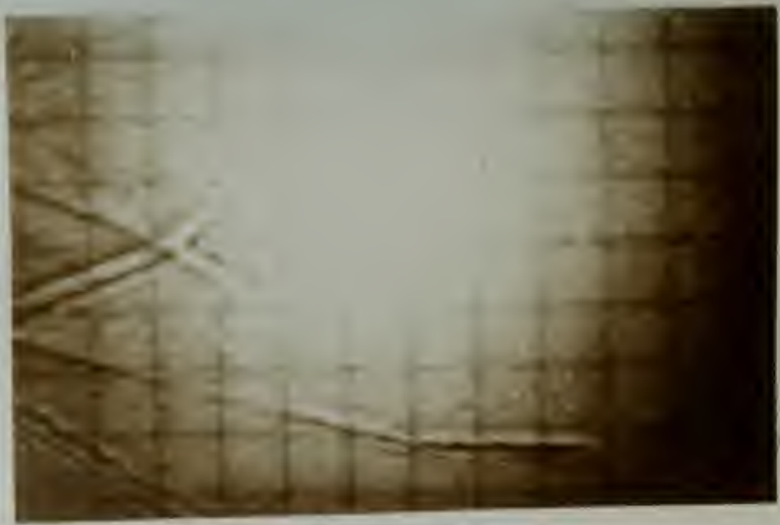


FIG 12
EFFECT OF UNSTEADY FLOW ON
WATER HEIGHT IN CHANNEL
M=1 STEADY FLOW
M=4 UNSTEADY FLOW
16
12
8
4
0
4
8
12
16
20
24
28
32
36
DISTANCE FROM CENTERLINE (IN)
DISTANCE DOWNSTREAM FROM JET (IN)
DIFFERENCE IN MAXIMUM AND MINIMUM WATER HEIGHT



a. Gate starting to open.

b. Gate completely open.

c. Gate partially closed.

d. Gate completely closed.

Fig. 13. Unsteady jet flow mixing with steady channel flow. M = 1 Steady flow. M = 4 Unsteady flow.

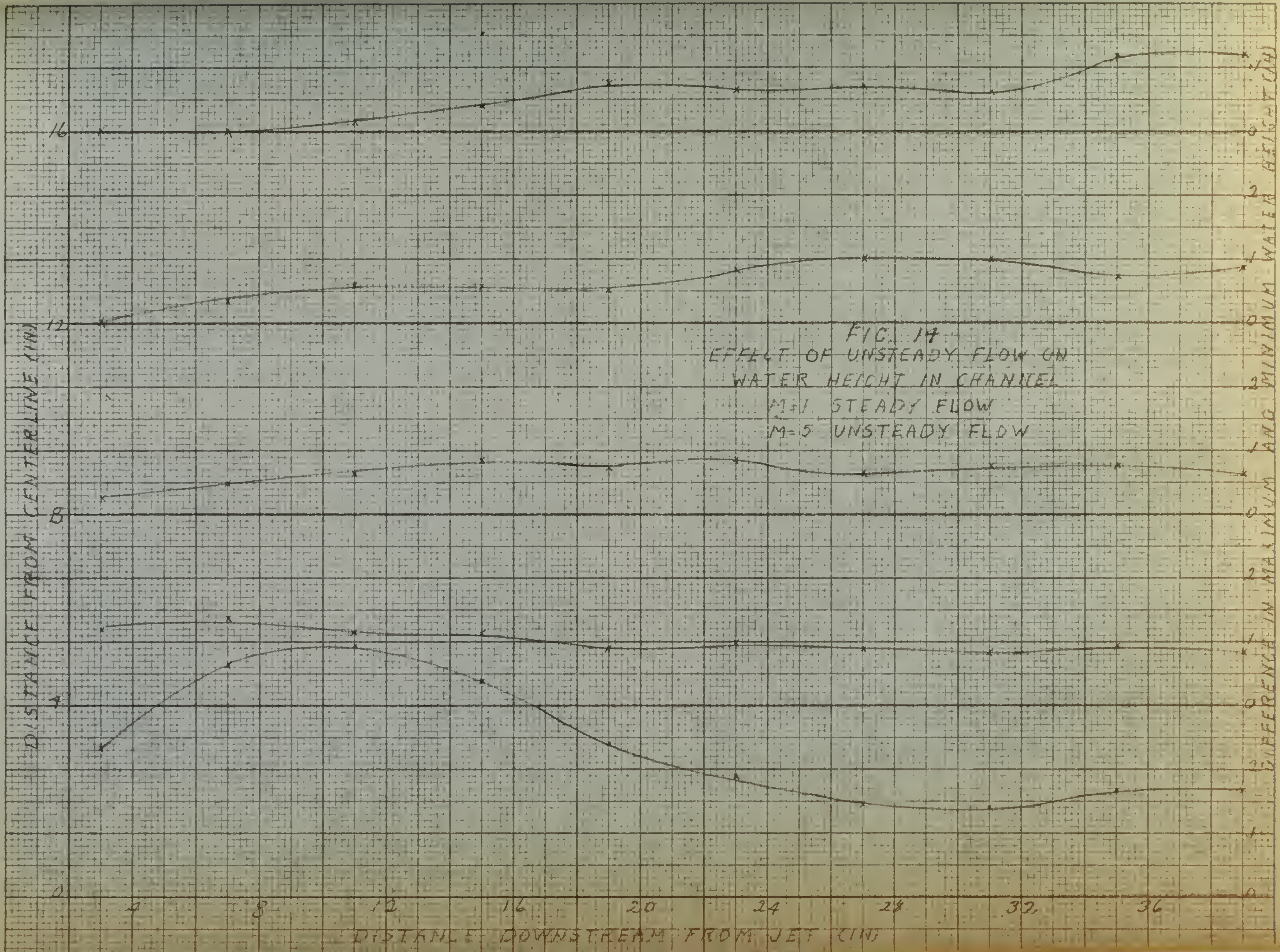


FIG. 14
EFFECT OF UNSTEADY FLOW ON WATER HEIGHT IN CHANNEL

a. Gate starting to open.

b. Gate completely open.

c. Gate partially closed.

d. Gate completely closed.

Fig. 15. Unsteady jet flow mixing with steady channel flow. $M = 1$ Steady flow. $M = 5$ Unsteady flow.

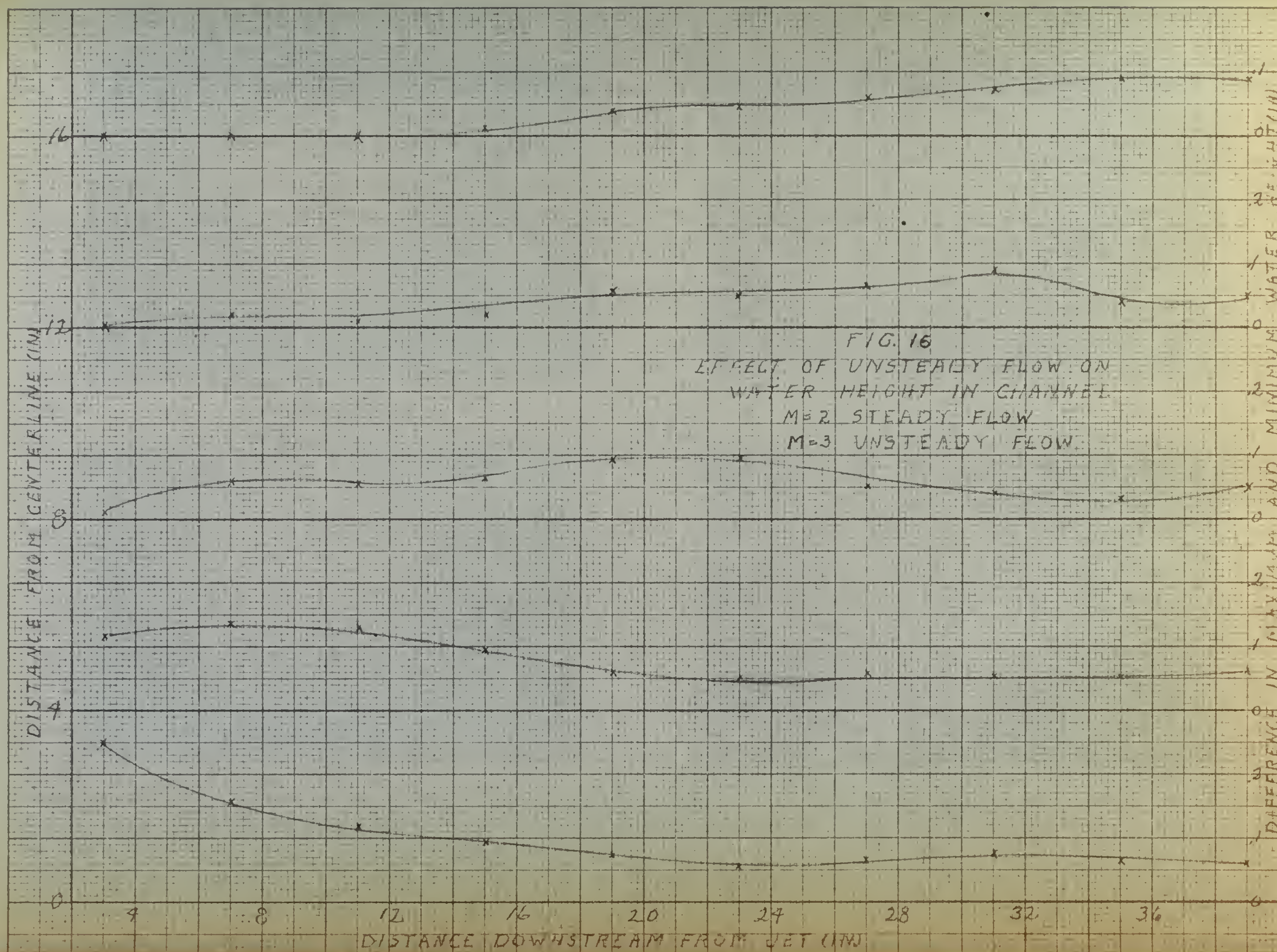
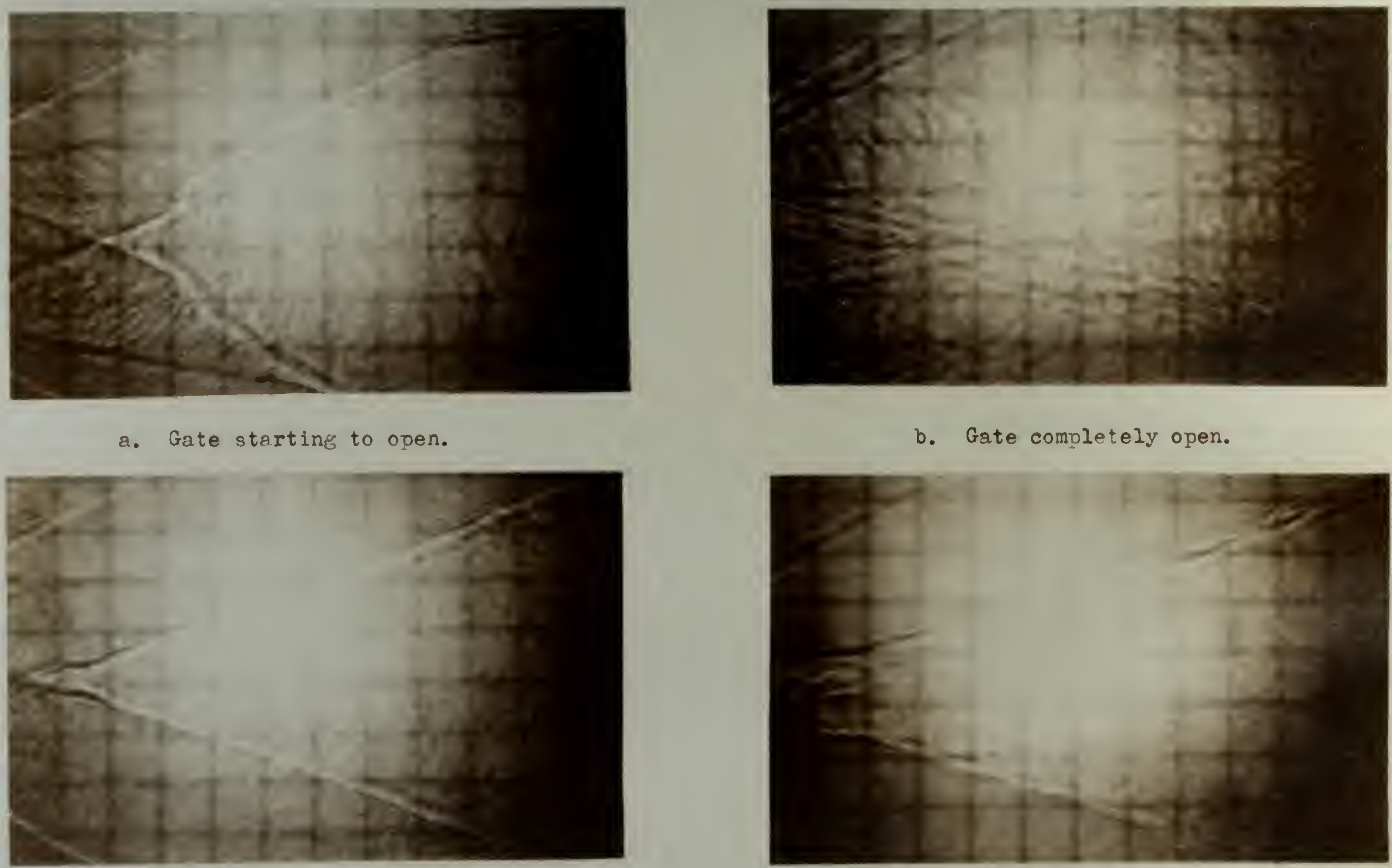


FIG. 16
EFFECT OF UNSTEADY FLOW ON
WATER HEIGHT IN CHANNEL
M=2 STEADY FLOW
M=3 UNSTEADY FLOW
DISTANCE FROM CENTERLINE (IN)
DIFFERENCE IN MAXIMUM AND MINIMUM WATER HEIGHT (IN)
DISTANCE DOWNSTREAM FROM JET (IN)
0
4
8
12
16
20
24
28
32
36



a. Gate starting to open.

b. Gate completely open.

c. Gate partially closed.

d. Gate completely closed.

Fig. 17. Unsteady jet flow mixing with steady channel flow. M = 2 Steady flow. M = 3 Unsteady flow.

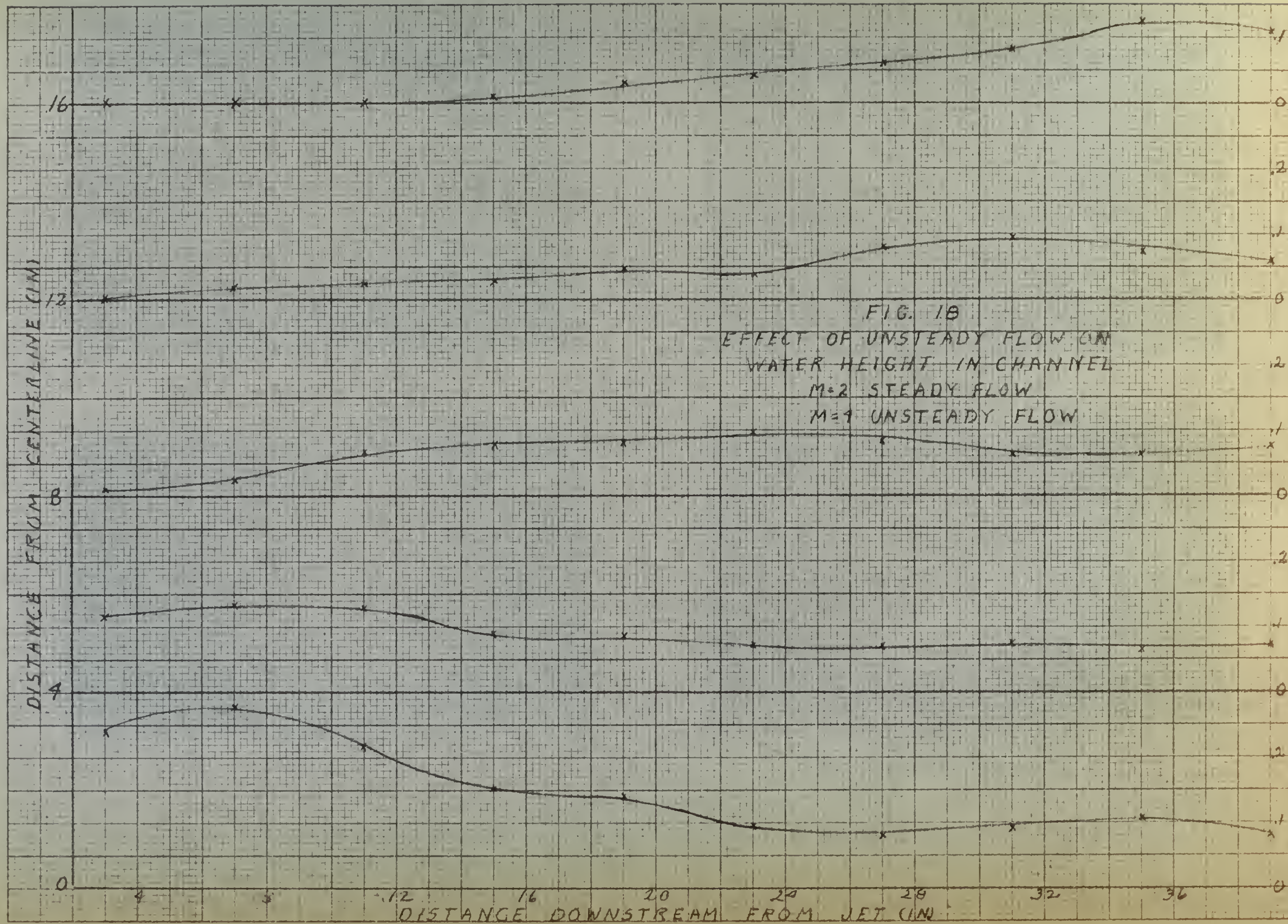


FIG. 18
EFFECT OF UNSTEADY FLOW ON WATER HEIGHT IN CHANNEL
M=2 STEADY FLOW
M=1 UNSTEADY FLOW

a. Gate starting to open.

b. Gate completely open.

c. Gate partially closed.

d. Gate completely closed.

Fig. 19. Unsteady jet flow mixing with steady channel flow. M = 2 Steady flow. M = 4 Unsteady flow.

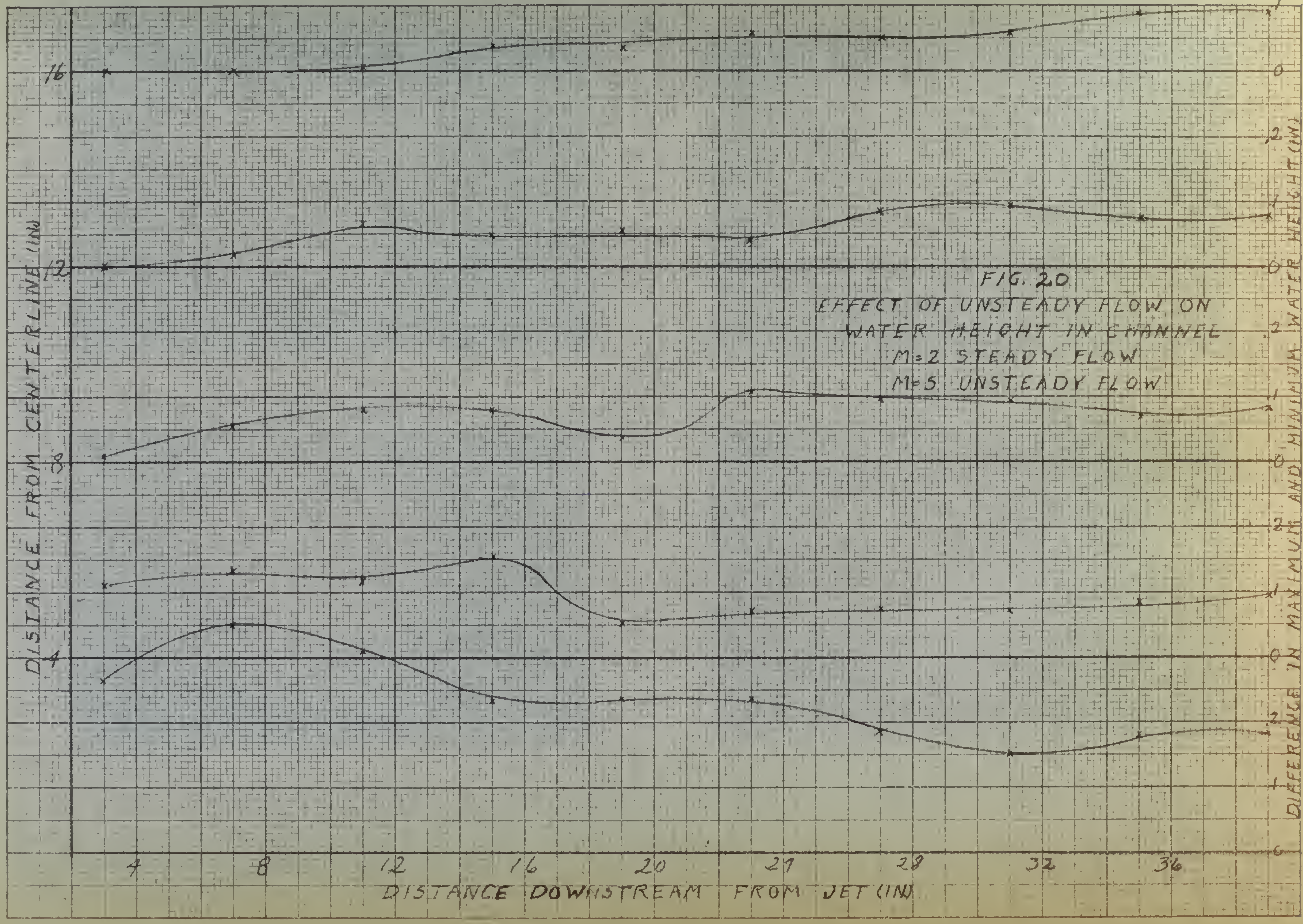


FIG. 20
EFFECT OF UNSTEADY FLOW ON
WATER HEIGHT IN CHANNEL
M=2 STEADY FLOW
M=5 UNSTEADY FLOW
DISTANCE FROM CENTERLINE (IN)
16
12
8
4
DISTANCE DOWNSTREAM FROM JET (IN)
4
8
12
16
20
24
28
32
36
DIFFERENCE IN MAXIMUM AND MINIMUM WATER HEIGHT (IN)

a. Gate starting to open.

b. Gate completely open.

c. Gate partially closed.

d. Gate completely closed.

Fig. 21. Unsteady jet flow mixing with steady channel flow. M = 2 Steady flow. M = 5 Unsteady flow.

SYMBOLS

a	velocity of sound
A	wave propagation velocity in water
d	height of water above floor at test section entrance
d_o	stagnation depth of water
g	acceleration due to gravity
M	Mach number
p	local pressure
p_o	stagnation pressure
T	local temperature
T_o	stagnation temperature
ρ	density of fluid
ρ_o	stagnation density
V	velocity of water
γ	ratio of specific heat at constant pressure to specific heat at constant volume

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